High Resolution Parallel Coastal Ocean Modeling: a Large Eddy Simulation Tool

Robert L. Street
Department of Civil and Environmental Engineering
Stanford University
Stanford, CA 94305-4020
phone: (650) 723-4969 fax: (650) 725-39720 e-mail: street@stanford.edu

Grant #: N00014-02-1-0204
http://www-ce.stanford.edu/faculty/street/

LONG-TERM GOALS

Our goal is to create a robust and highly efficient nonhydrostatic code that can be applied in a predictive manner to littoral zones and bays on a spatial scale of the order of 100 km and time scales of the order of days to weeks. The product will be a user-oriented production code for the coastal environment.

OBJECTIVES

This project aims to synthesize a number of computational and numerical tools to produce an innovative and powerful coastal ocean simulation tool to generate accurate predictions of motions and transport in coastal oceans under conditions when a nonhydrostatic and terrain-following representation is essential. Another primary objective is to apply the best algorithms available to create a simulation code that is capable of representing the physical processes at high resolution and capable of very high speed on multiple-processor parallel computers.

APPROACH

This project is complementary to NSF ITR Grant OCE-0113111. That project is focused on creation of a new generation computer code and application of it to internal waves in Monterey and Mamala Bays. Four faculty are involved. Robert Street is the PI. Margot Gerritsen is an expert on numerical methods and adaptive mesh refinement strategies. Mark Merrifield is a member of the HOME project and will provide the data for Mamala Bay and assist in its interpretation. The main code development is supported by the NSF ITR project and Oliver Fringer is carrying out the development work. This ONR funding is supporting a doctoral student to take responsibility for applications. This entails the crucial task of generation of grids and initial data and boundary forcing. He is carrying out and analyzing production runs as well.

We will employ numerical large-eddy simulation to generate accurate predictions of motions and transport in coastal oceans under conditions when a nonhydrostatic and terrain-following representation is essential. The simulation should be able to handle all processes from the free-surface to the bed so that the whole range from surface waves through internal waves to sediment motions can be simulated. Two specific applications of the completed code are planned. Both involve nonhydrostatic evolution of internal tides. The first is in Monterey Bay, California, where solitons are expected to form and the internal tide signal is intensified in the bottom of the Monterey Canyon. The

Report Documentation Page						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **High Resolution Parallel Coastal Ocean Modeling: a Large Eddy Simulation Tool**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Civil and Environmental Engineering,,Stanford University,,Stanford,,CA, 94305**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		

14. ABSTRACT

Our goal is to create a robust and highly efficient nonhydrostatic code that can be applied in a predictive manner to littoral zones and bays on a spatial scale of the order of 100 km and time scales of the order of days to weeks. The product will be a user-oriented production code for the coastal environment.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

second is in Mamala Bay, Hawaii, where high-amplitude and nonlinear internal tides are observed and there are key questions to be answered about the nature of these waves and their behavior in the Bay.

From a numerical point of view our approaches include:

1. Parallel processing: We are using MPI, the message passing interface.
2. Free-surface and nonhydrostatic Poisson-equation solvers: We are exploring the use of *PETSc [Portable Extensible Toolkit for Scientific Computing*; see below].
3. Accurate advection: We are employing mass, volume, momentum and energy conserving Eulerian schemes.
4. Large Eddy Simulation: We have developed and tested a mixed subfilter-scale model for turbulence.
5. State of the art gridding: Produces high quality unstructured grids in the horizontal and structured in the vertical for optimal compromise between efficiency and flexibility/grid quality.

WORK COMPLETED

For Fiscal Year 2003, the primary tasks under this ONR grant were the analysis and preparation of highly resolved unstructured grids for Monterey Bay and to begin production runs of the parallel code to study internal waves in idealized shelf geometries and Monterey Bay. Currently, we are using a three-dimensional primitive equation version of our unstructured-grid code and are testing its ability to (1) generate internal waves at the shelf break in simplified geometries and (2) compute the hydrostatic internal wave spectrum in Monterey Bay. The code employs the momentum and energy conserving Eulerian formulation of Perot (2000) for advection of momentum, and the mass conserving formulation of Gross et al. (2002) for scalar advection. The Poisson equations resulting from the semi-implicit free-surface formulation (Casulli, 1998) and the nonhydrostatic pressure are being solved with the preconditioned conjugate gradient algorithm. Prof. Gerritsen is exploring the use of *PETSc* to parallelize and optimize these solvers.

RESULTS

Advection schemes

A significant amount of work this year has focused on the choice of the advection scheme for momentum. Currently we are employing a momentum and energy conserving Eulerian formulation (Perot, 2000) for unstructured, staggered grids. The original intent was to employ the Euler-Lagrange formulation of Casulli (1998) with Kriging (LeRoux et al. 1997) as the interpolator. However, because the parallel formulation limits the Courant number to less than unity to prevent Euler-Lagrange tracebacks from moving into a neighboring processor, it was decided that an Eulerian formulation would be more appropriate.

Treatment of the bottom boundary

We have also analyzed the treatment of the bottom boundary carefully in order to determine an appropriate means of accurately representing the bottom bathymetry. The current formulation employs the semi-implicit free-surface formulation of Casulli (1998), which requires a stair-stepped treatment of the bottom bathymetry. While this formulation removes the false baroclinic pressure gradients associated with sigma coordinate grids, the trade off introduces errors in along-slope gradients which

are not as well resolved with stair-stepped grids. The shaved cell approach of Adcroft et al. (1997) was considered, but this approach, along with other similar cut-cell techniques (e.g. Kirkpatrick et al., 2003) is not feasible when wetting and drying is desired. The original intent was to employ the immersed boundary method (IBM), which has been employed by Tseng and Ferziger (20003) for geophysical applications and showed improvement over stair-stepped grids. Despite their favorable results, we have continued to use our stair-stepped formulation because, as opposed to the IBM method, it guarantees conservation of mass and volume, and we are wary of the use of non-conservative schemes for the high Reynolds number flows encountered in our application where a drag law must be used to model the shear stress at the bottom bathymetry. We will continue to search for improved conservative bottom-following formulations.

Grid generation

Unstructured grid generation has proven to be a complex task because a triangulation in which the elements are generated to follow or resolve certain regions of the complex bathymetry of Monterey Bay always results in degenerate triangles. Triangles are considered degenerate when the Voronoi points (which are the centers of the circumcircles of the triangle vertices) lie outside of the triangles because of the creation of obtuse triangles. While it is possible to minimize the frequency of degenerate triangles by specifying the minimum angle allowed in a triangulation, the Delaunay triangulation of Shewchuck (2002) is guaranteed to converge only when the minimum angle is less than 33.8^0. As an example, Figure 1 depicts a triangulation of Monterey bay in which triangle faces are coincident with chosen isobaths. From the figure, it is clear that an arbitrary choice of isobaths results in degenerate triangles, especially when isobaths are very close together, in which case large area ratios between neighboring triangles are also generated.

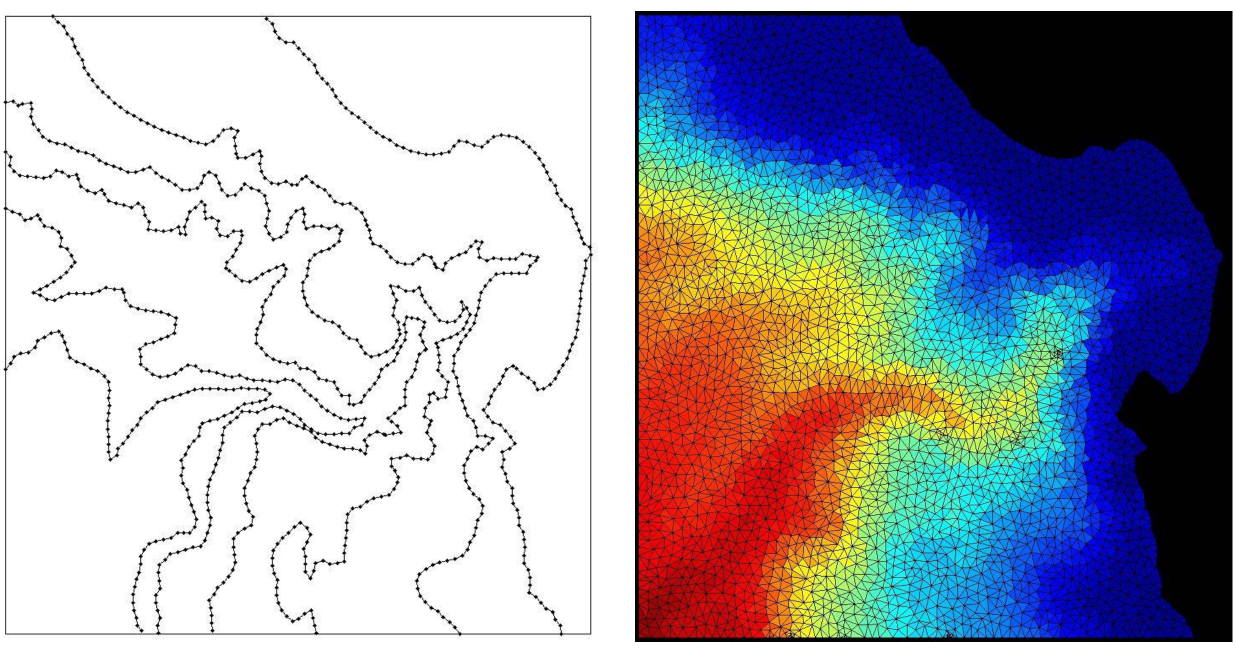

Figure 1. Isobaths at 0, 345, 1122, 1760, 2416, and 2796 m and the associated Voronoi triangulation for which the isobaths coincide with triangle faces.

An alternative is to employ BatTri (Bilgili and Smith, 2001), a front-end for Triangle, which allows the user to select regions of the bathymetry for improved refinement. Examples of using BatTri are shown

in Figure 2. It can be seen that, while refinement is achieved in a straight-forward manner, the transition of grid area across the refinement boundary is much too high. While Triangle does allow the minimum angle constraint, it does not allow a constraint on the maximum area ratio. As it is, Triangle can be used as a library function directly in the main code, but the BatTri routines cannot be employed directly because they are a front-end to Triangle and are written in Matlab. We are considering the GAMBIT (Fluent, Inc, 2001) unstructured grid generating package, which will hopefully resolve these issues.

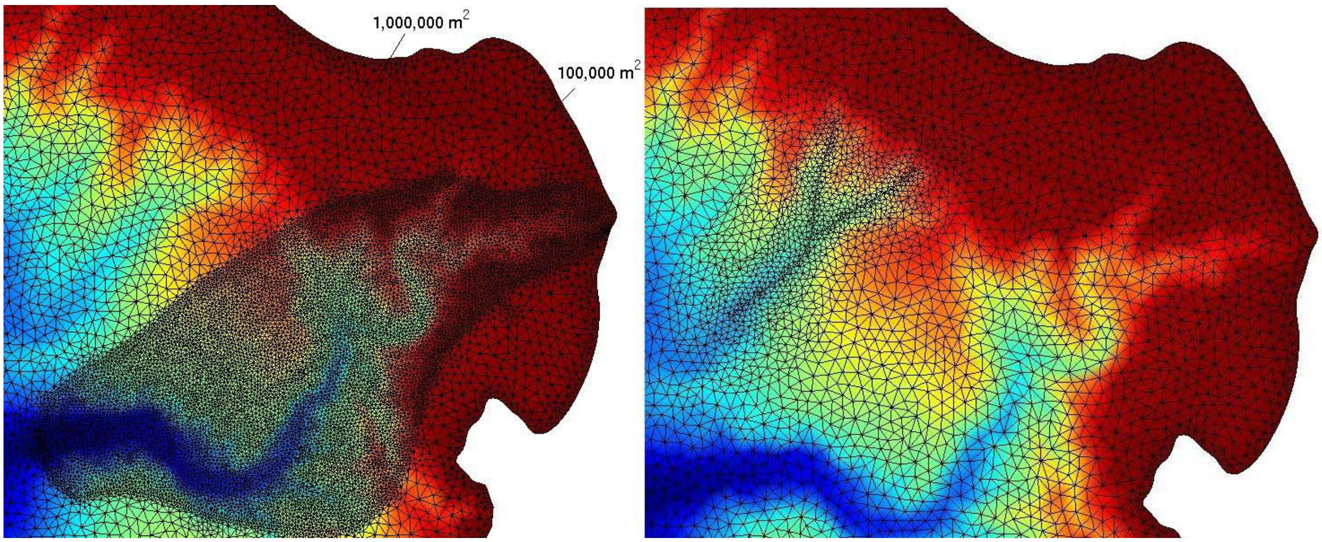

Figure 2. Examples of using the front end to BATTRI, showing the result of refining a region of the bay as well as imposing a constraint on the triangulation to follow the canyon bathymetry

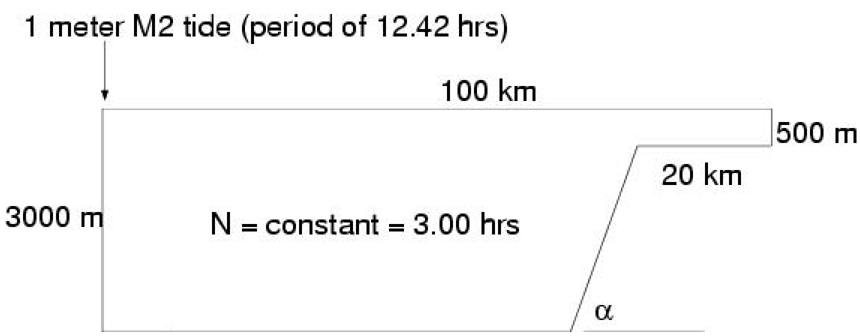

Figure 3. The simplified two-dimensional shelf-break bathymetry, showing the forcing and buoyancy frequencies. The effect of varying the slope angle α is shown in Figure 4.

Internal waves in idealized geometries

To verify the capability of the code to generate internal waves at a shelf break, we have tested it using the simplified coastal shelf bathymetry shown in Figure 3. The stratification is linear with a constant buoyancy period $2\pi/N$ of 3 hours. The results of forcing the left boundary with an M2 tidal amplitude of 1 m ($2\pi/\omega$=12.42 hours) and four different slope angles α are shown in Figure 4. Consistent with the linearized dispersion relation which determines the propagation angle of the group velocity vector,

the internal waves propagate away from the shelf break at an angle given by $\sin^{-1}(\omega/N)=14.3^0$. The four different shelf-break slopes in Figure 4 are given by 9.5^0 (subcritical), 14.3^0 (critical), 26.6^0 (supercritical), and 90^0 (vertical). The seaward propagating depth-integrated energy flux is shown for each case as a multiple of the energy flux for the critical case, E_c. The results in Figure 4 show that the energy flux increases as the slope angle increases beyond the critical slope. This results from the increase in the vertical velocity at the shelf break as the slope angle increases, which is directly related to the strength of the internal wave generation zone at the shelf break. Internal wave generation is weakest for the subcritical slope, but energy flux is also reduced because the subcritical slope impedes seaward propagation of internal wave energy. Numerical oscillations are pronounced in the vertical slope case because of the sharp discontinuity in the bathymetry.

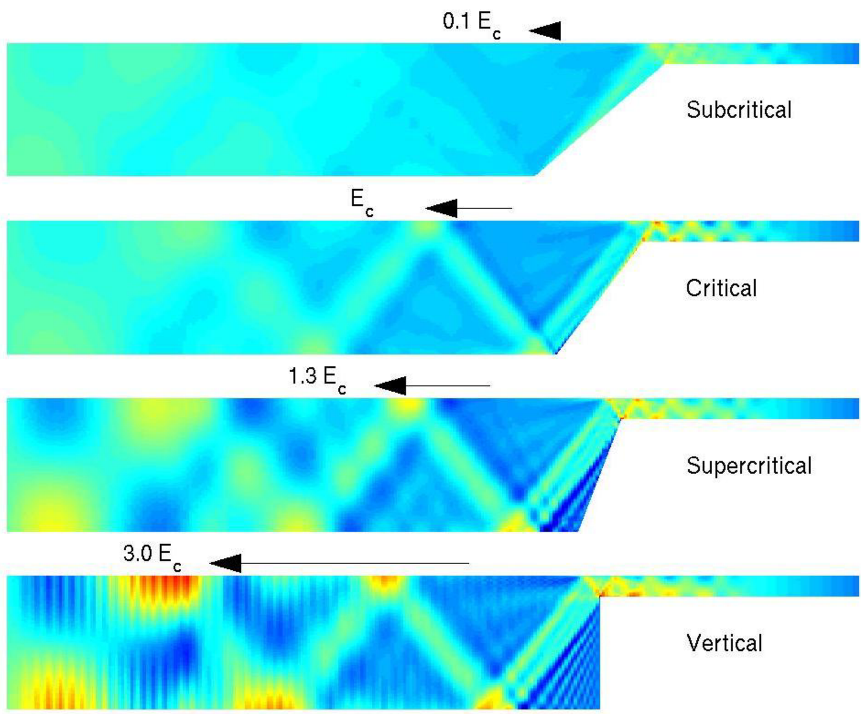

Figure 4. Perturbation density fields resulting from the generation of an internal tide at a shelf break, showing the depth-integrated energy flux for each case.

IMPACT/APPLICATIONS

A key goal is to produce a production-style code, i.e., one that can be used by others, is fully documented and tested, and in the public domain. Thus, a result will be a robust tool for use by the coastal oceanographic community to study coastal processes.

Previous studies have documented the importance of gaining an understanding of the generation, propagation, and fate of internal tidal waves on the continental shelf and coastal bays. Definitive answers about the role of these waves would materially increase our understanding of the mixing and transport on the shelves and in the bays and their influence on sediment transport. Hence a predictive capability has broad coastal oceanographic applications, including for example, to the modeling phase of the HOME project.

RELATED PROJECTS

NSF OCE-0113111 High Resolution Coastal Ocean Modeling. The numerical code for this ONR project is being created under the NSF grant.

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HONORS/AWARDS/PRIZES

Oliver B. Fringer, Stanford University. 2003 Frederick A. Howes Memorial Scholar in Computational Science, Krell Institute, Department of Energy.